

Near-Infrared Spectroscopy of SN 2009ip’s 2012 Brightening Reveals a Dusty Pre-Supernova Environment

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ABSTRACT

We present low-resolution near-infrared (IR) 0.8–2.5 μm spectra of Supernova (SN) 2009ip, taken immediately before, during, and just after its rapid brightening in late September/October 2012. The first epoch shows the same general spectral characteristics as the later epochs (smooth continuum, narrow H and He I emission lines), but the IR continuum shape is substantially redder than the later epochs. The epoch 1 continuum can be approximated by reddening the peak-luminosity (epoch 3) spectrum by $E(B - V) = 1.0$ mag, but the blue color seen in visual-wavelength spectra at the same time indicates that strong wavelength-dependent extinction by circumstellar dust is not the correct explanation. Instead, we favor the hypothesis that the redder color before the brightening arises from excess emission from hot ~ 2000 K circumstellar dust. The minimum radius ($\gtrsim 120$ AU) deduced from the dust temperature and observed luminosity of the transient, combined with the observed expansion speed in the precursor outbursts of SN 2009ip, is consistent with an ejection at least 1.1 yr earlier. The mass of hot dust indicated by the IR excess is $\sim 4 \times 10^{-7} M_{\odot}$, although this is only a lower limit since the near-IR data do not constrain the mass of cooler dust. Thus, the observed pre-SN outbursts of this object were able to efficiently form dust into which the SN ejecta and radiation now propagate. This is consistent with the notion that the same pre-SN eruptions that generally give rise to SNe IIn also give rise to the dust needed for their commonly observed IR echoes. We also discuss some aspects of the IR line profiles, including He I $\lambda 10830$.

Key words: circumstellar matter — stars: variables: other — stars: winds, outflows — supernovae: general — supernovae: individual (SN 2009ip)

1 INTRODUCTION

Supernova (SN) 2009ip provided a truly remarkable sequence of events, first noted as a SN “impostor” or eruption of a luminous blue variable (LBV) in 2009 (Smith et al. 2010), and then subsequently observed as a core-collapse SN in mid/late 2012 (Mauerhan et al. 2013). It joins SN 1987A (Walborn et al. 1989; Rousseau et al. 1978) as the only SN for which we have a direct detection *and a spectrum* of the progenitor star. In the case of SN 2009ip, however, we have a much more detailed record and higher quality data pertaining to its unstable pre-SN state. It is reminiscent of the pre-SN outburst seen 2 yr before SN 2006jc (Pastorello et al. 2007), but in that case only one outburst was detected and

no spectrum was obtained. A brief recounting of SN 2009ip’s pre-SN activity is as follows:

After the discovery of SN 2009ip as a new transient source in August 2009 (Maza et al. 2009), it was recognized that it was not a true SN, but was instead a non-terminal eruptive transient similar to LBVs. Smith et al. (2010) presented archival *Hubble Space Telescope* (*HST*) images, archival ground-based photometry, and new photometry and spectra of the outburst. *HST* data revealed that 10 yr prior to discovery, the quiescent progenitor was a luminous supergiant with $L \simeq 10^6 L_{\odot}$ and a likely initial mass of around 50–80 M_{\odot} , while the archival ground-based photometry documented a ~ 5 yr long S Dor-like LBV phase that preceded the 2009 discovery. The 2009 outburst itself had a peak absolute magnitude of around -14.5 (Smith et al. 2010), similar to giant LBV eruptions (Smith et al. 2011). Spectra of the 2009 outburst showed strong Balmer emis-

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sion lines similar to LBV eruptions (e.g., Smith et al. 2011), indicating an expansion speed of order 550 km s^{-1} . The 2009 outburst of SN 2009ip was unusual compared to most LBV-like eruptions, however, due to the rapid brightening and fading over a few weeks instead of a few months to years (Smith et al. 2011). Foley et al. (2011) presented additional spectra and a reanalysis of the archival *HST* data that reinforced these conclusions. After these first papers on the 2009 outburst, SN 2009ip then had another outburst of similar magnitude in 2010 (Drake et al. 2010), and it has recently been reported (Pastorello et al. 2013) that it had additional eruptions of similar brightness since then as well.

On 2012 July 24 (UT dates are used throughout this paper), SN 2009ip was discovered to have yet another outburst (Drake et al. 2012). This new outburst was of similar magnitude to the previous ones, and at first it was assumed that this was yet another LBV-like eruption. Foley et al. (2012) reported that an early spectrum obtained on 2012 Aug. 24 was consistent with spectra of the previous LBV-like outbursts, with line widths around 600 km s^{-1} . However, spectra obtained later on 2012 Sep. 7-16 (Smith & Mauerhan 2012) revealed a transformation in the spectrum of SN 2009ip, which now showed very broad Balmer emission and absorption lines out to speeds of $13,000 \text{ km s}^{-1}$. These broad features indicated that the impostor SN 2009ip was becoming a true core-collapse SN (Mauerhan et al. 2012), since these spectral features had never been seen previously in this object or any LBV eruption. Pastorello et al. (2013) have pointed out that broad features were seen previously, but these were only seen in absorption (as noted earlier by Smith et al. 2010 and Foley et al. 2011), while emission-line components of SN 2009ip had always shown narrow or intermediate-width emission lines prior to Sep. 2012. Small amounts of very fast material have been seen around LBVs, as in the case of η Carinae (Smith 2008), but the bulk velocity of most of the ejected mass in LBV eruptions is much slower.

The broad emission lines in SN 2009ip were first noted in Sep. 2012, around the time of peak luminosity for the precursor outburst (see Figure 1). The object faded over the next week or so, but then brightened very suddenly, rising ~ 3 mag in a few days. This very rapid brightening was probably caused by the fast SN ejecta crashing into slower circumstellar material (CSM) ejected by the precursor eruptions (Mauerhan et al. 2013). Prieto et al. (2013) presented exceptionally high-cadence photometry of this very rapid brightening phase, also concluding that this was most likely due to the onset of SN-CSM interaction similar to other SNe IIn. Indeed, as it reached peak luminosity, the spectrum took on the character of a normal SN IIn with a smooth blue continuum and Balmer lines exhibiting narrow line cores and Lorentzian scattering wings (Mauerhan et al. 2012). Levesque et al. (2013) have recently presented additional spectra of the SN, highlighting aspects of its Balmer decrement. SN 2009ip gives vivid confirmation of the idea that very massive and eruptive LBV-like stars can explode to produce SNe IIn (e.g., Smith et al. 2007, 2008a, 2011; Gal-Yam et al. 2007; Gal-Yam & Leonard 2009).

In Figure 1 we also plot the light curve of SN 2010mc for comparison, recently reported by Ofek et al. (2013). Ofek et al. discussed the remarkable detection of a precursor outburst in this Type IIn event as well, but they did not note

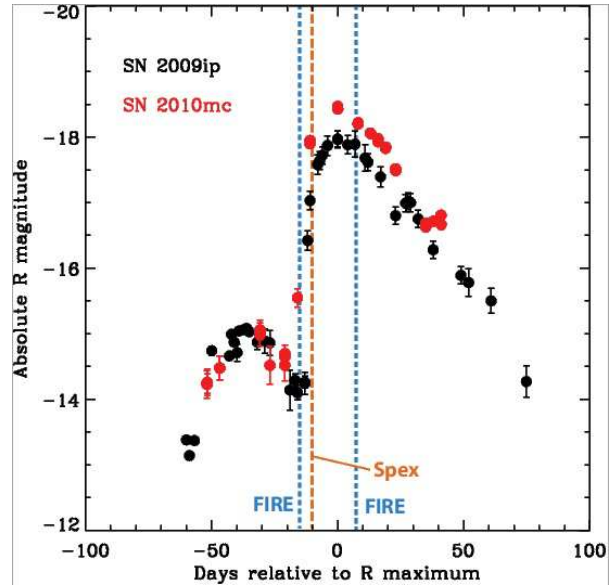


Figure 1. Absolute *R*-band magnitude light curve of SN 2009ip (black points) from Mauerhan et al. (2012); but with the three earliest points taken from Pastorello et al. (2013), showing the dates of our FIRE and Spex spectra relative to the time of maximum luminosity (see Table 1). The red points show the recently published light curve of SN 2010mc from Ofek et al. (2013a), which appears to have an almost identical luminosity evolution (i.e., the absolute *R*-band magnitude of SN 2010mc was not scaled).

Table 1. Infrared Spectroscopy of SN 2009ip

Date (y-m-d)	Day (max)	Tel./Instr.	R	$\Delta\lambda$ (μm)
2012-09-22	-15	Magellan/FIRE	300-500	0.8-2.5
2012-09-27	-10	IRTF/Spex	120	0.7-2.5
2012-10-14	+7	Magellan/FIRE	300-500	0.8-2.5

the uncanny similarity to the light curve of SN 2009ip (which was still underway as their paper was in preparation). Figure 1 emphasizes that *these two objects are nearly identical* in terms of peak luminosities and timescales for both the precursor and SN outbursts (the absolute magnitudes have not been adjusted). Since most SNe IIn observed thus far have been discovered near peak and lack high-quality pre-SN observations, it may be the case that the erratic pre-SN variability of SN 2009ip is not so unusual.

Here we present near-IR spectra of the remarkable 2012 explosion of SN 2009ip. We discuss implications for the dusty environment produced by the precursor LBV eruptions, as well as aspects of the line profiles.

2 OBSERVATIONS

We obtained three IR spectra of SN 2009ip, which were taken immediately before its fast rise in brightness, during the rise, and around the time of peak luminosity. Figure 1 shows the three epochs of our spectroscopy relative to the light curve of SN2009ip's 2012 outburst from Mauerhan et al. (2012). Observational information is listed in Table 1,

and the resulting spectra are plotted in Figure 2. All spectra in Figure 2 (plotted in black) have been corrected for an assumed Galactic reddening value of $E(B - V) = 0.019$ mag, following Smith et al. (2010).

Our first near-IR spectrum was obtained on 2012 Sep. 22 (UT) using the Folded-port InfraRed Echellette spectrograph (FIRE; Simcoe et al. 2008, 2010) on the 6.5-m Magellan Baade Telescope. This was only 2 days prior to the dramatic rapid rise in brightness of SN 2009ip. The low-dispersion, high-throughput prism mode provides a spectrum that spans a wavelength range of 0.8–2.5 μm at a resolving power $\lambda/\Delta\lambda = 300$ –500. We completed an ABBA sequence on SN 2009ip, with an average airmass of 1.16, and immediately afterward obtained a spectrum of an A0 V standard star (HIP 113376) for flux calibration and telluric correction, as described by Vacca, Cushing, & Rayner (2003). Data were reduced using the FIREHOSE pipeline. Portions of this spectrum were presented and discussed by Ofek et al. (2013b) regarding relative line velocities. However, we noted that there may have been thin cirrus clouds during the observation of the standard star, which might affect the absolute flux calibration; because of this and possible slit losses that are difficult to quantify, the resulting flux-calibrated spectrum appeared brighter than indicated by simultaneous photometry, so the spectrum is scaled down in Fig. 2.

A second epoch of low-resolution near-IR spectra for SN 2009ip were obtained with the SpeX spectrograph (Cushing et al. 2004) on the NASA Infrared Telescope Facility (IRTF) on 2012 Sep. 27 (UT) in clear conditions with 0''.5 seeing. This spectrum was taken during the rapid rise, well before SN 2009ip had reached its peak luminosity, and an initial report was given by Burgasser et al. (2012). The prism-dispersed mode and 0''.5 slit (aligned with parallactic) were used, providing 0.7–2.5 μm coverage with resolution $\lambda/\Delta\lambda \approx 120$, and dispersion of 20–30 \AA pixel^{-1} . Eight exposures were obtained in an ABBA pattern at an average airmass 1.52, for a total exposure of 840 s. The nearby A0 V star HD 202941 ($V = 7.05$ mag) was observed immediately after for flux calibration and telluric absorption correction, along with internal flat field and arc lamp exposures. Data were reduced with the IDL SpeXtool package, version 3.4 (Vacca et al. 2003; Cushing et al. 2004), using standard settings.

Our third epoch was obtained on 2012 Oct. 14 (UT), once again using FIRE on Magellan. The low-resolution instrumental setup, observations of an A0 V standard, and data reduction procedures were nearly the same as described above for the previous FIRE epoch, except that we used a different standard star (HD 219341).

3 DUST AND THE IR CONTINUUM SHAPE

A striking aspect of the spectral sequence in Figure 2 (top) is that the first-epoch spectrum on Sep. 22 is substantially different from those on Sep. 27 and Oct. 14, which appear qualitatively very similar to each other. One particular difference is in the continuum shape. For comparison, representative blackbody curves (blue) are plotted along with each epoch of the observed spectra, suggesting that the apparent color temperature increases from ~ 3400 K on Sep. 22, to 6000 K and 7500 K on the two later epochs. Continuum slopes matching temperatures of 6000–7500 K are typ-

ical for SNe II_{in}, and the spectral characteristics (strong H lines) are consistent with that range of temperatures. However, the much lower temperature of 3400 K implicated by the IR continuum slope on Sep. 22 is not commensurate with the presence of He I and H emission lines in the spectrum. Therefore, a cooler photospheric temperature is not the likely explanation for the continuum shape (the 3400 K blackbody underpredicts the flux near 1 μm anyway). Two possible alternatives involving dust are discussed below.

First, a redder color on Sep. 22 than at later times could potentially arise from significant reddening by CSM dust, which is destroyed at later epochs as the SN brightens and the shock expands. The orange curve in Figure 2 (top panel) shows the Oct. 14 spectrum reddened by $E(B - V) = 1.0$ mag, providing a satisfactory match to the shape of the observed spectrum on Sep. 22. This is unlikely to be the real explanation for the observed color, however, because the amount of reddening required to match the IR continuum shape would cause even more severe reddening at visual wavelengths. This is demonstrated in the bottom panel of Figure 2, where we plot visual-wavelength spectra taken 1–3 days later (already published by Mauerhan et al. 2013) alongside the Sep. 22 FIRE spectrum. The two orange curves (solid and dashed) show hot blackbodies (7500 and 13,000 K, respectively) that are reddened to approximate the shape of the near IR continuum, using $E(B - V) = 1.0$ and 1.5 mag, respectively. While these reddened blackbodies seem to match the IR continuum shape, the flux at visual wavelengths fall far below the observed visual wavelength spectra taken only 1 and 3 days later (note that these visual spectra have been adjusted in flux by a few per cent so that the ~ 9000 \AA fluxes match the IR spectra, correcting for the fact that SN 2009ip was variable).

Instead of reddening, a more likely explanation for the IR color is an extra contribution from *emission* of dust instead of absorption. The magenta spectrum plotted against the observed Sep. 22 spectrum is, once again, the spectrum near peak on Oct. 14, but with an added contribution from hot dust emission (Fig. 2, top panel). For simplicity, we used a 2000 K blackbody modified by λ^{-1} emissivity. When added to the Oct. 14 spectrum, it matches the overall shape of the Sep. 22 near-IR continuum very well. The bottom panel of Figure ?? shows that the combination (magenta curve) of a hot blackbody (13000 K, blue) and the same 2000 K dust component (green dashed) can match both the visual wavelength and IR spectra simultaneously. The fact that the visual-wavelength continuum requires a hotter blackbody (13,000) than the temperature implied by fitting the IR continuum alone (7500K) merely reflects that fact that IR wavelengths on the Rayleigh-Jeans tail of a Planck function are a less sensitive probe of the underlying hot component.

This IR excess presumably arises from CSM dust heated by the luminosity of the precursor transient source, as in an “IR echo”. Dust at around this temperature is as hot as dust can be, residing at the innermost radius of the dust shell, inside of which the dust is destroyed.¹ This general

¹ Note that a high dust temperature near 2000 K does not necessarily indicate C-rich dust, as is often assumed. Dust formed in the colliding-wind shock of η Carinae has a similar high temperature (Smith 2010) even though η Car is known to be severely

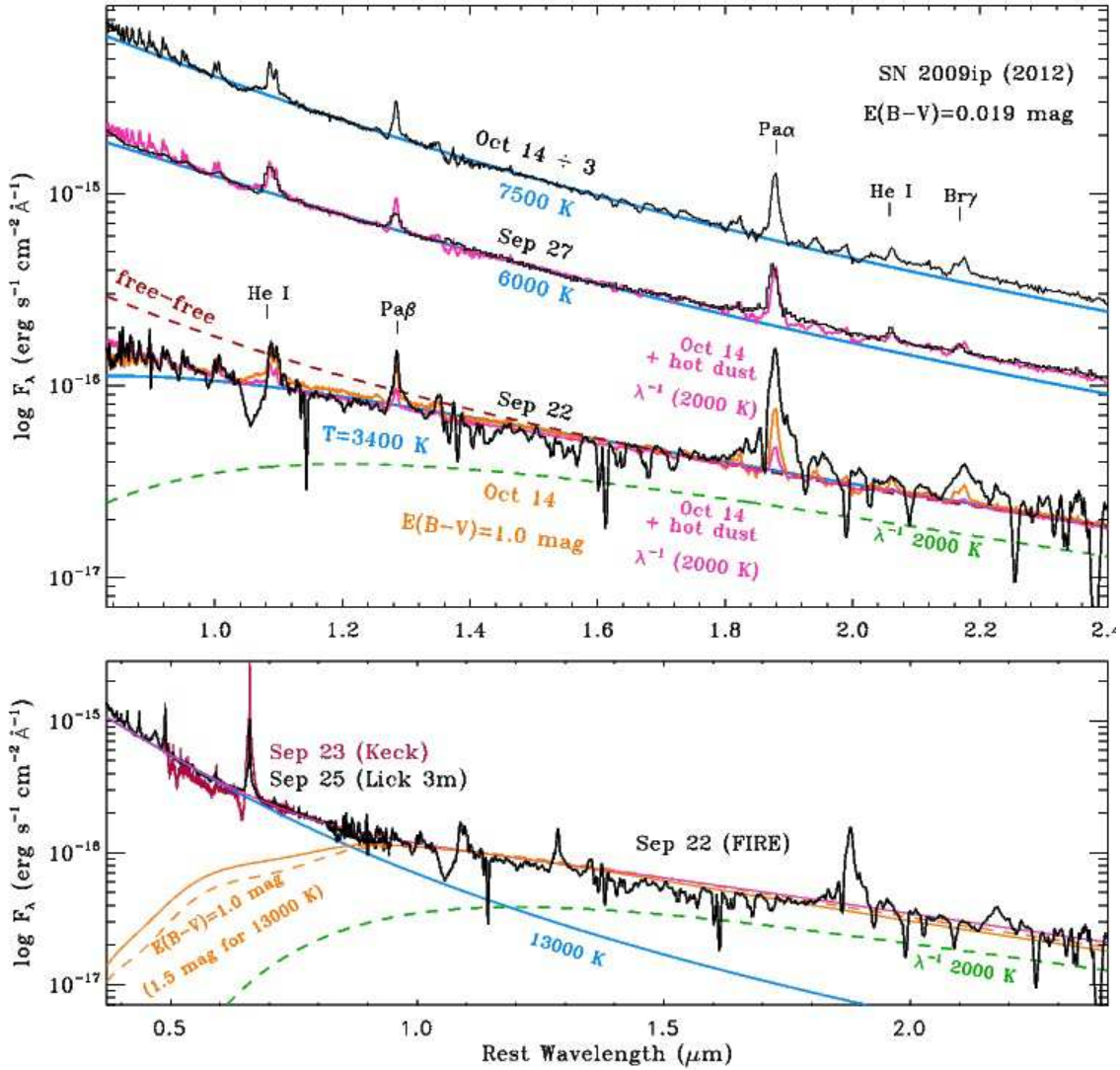


Figure 2. (Top) Near-IR spectra of SN 2009ip during the 2012 brightening. The black spectra are taken with Spex and FIRE on the dates indicated (see Table 1), corrected for Galactic reddening of $E(B - V) = 0.019$ mag (Smith et al. 2010). The colored curves show various possible interpretations to match the continuum shape: (1) the blue curves show representative blackbodies; (2) the orange spectrum shows the Oct. 14 spectrum (near peak luminosity) reddened by $E(B - V) = 1.0$ mag to match the continuum shape of the pre-SN spectrum on Sep. 22; (3) the two magenta spectra once again use the Oct. 14 spectrum, but this time the continuum shape is augmented by a 2000 K greybody with λ^{-1} emissivity, giving a rough example of how hot dust might add to the spectrum (the dust contribution is shown alone by the green dashed curve). The magenta spectrum matched to the Sep. 27 spectrum has less relative contribution from hot dust, and relatively more from the scaled Oct. 14 spectrum. (Bottom) The same Sep. 22 IR spectrum as in the top panel, but plotted alongside nearly simultaneous visual-wavelength spectra taken 1-3 days later, from Mauerhan et al. (2013). The shape of the combined optical/IR continuum is best explained by a 13,000 K blackbody (blue) plus the same 2000 K dust component as in the top panel (green dashed; the magenta curve is the addition of the two components). Also shown for comparison are a 7500 K blackbody reddened by $E(B - V) = 1.0$ mag (orange solid curve, as in the top panel) and a hotter 13,000 K blackbody reddened by 1.5 mag (orange dashed).

picture is similar to the IR echoes observed in many SNe, particularly common among SNe IIn (see Fox et al. 2011, and references therein) due to their dense and dusty pre-existing CSM. On Sep. 22 before the rapid brightening, SN 2009ip had a luminosity of roughly $L \simeq 4 \times 10^7 L_{\odot}$. CSM dust in equilibrium at 2000 K would then reside at a radius of

carbon deficient. For η Car, the hot dust is thought to be corundum (Al_2O_3), which condenses at a similar high temperature.

$$R \simeq 120 \text{ AU} \left(\frac{QL}{10^{7.6} L_{\odot}} \right)^{\frac{1}{2}} \left(\frac{T_d}{2000 \text{ K}} \right)^{-2} \quad (1)$$

(where Q is the ratio of the grain absorption to emission efficiency), which is around 120 AU for large grains that behave like blackbodies ($Q \simeq 1$), or somewhat farther from the star for smaller grain sizes that have larger values of Q . Equation (1) really provides a lower limit to the radius of the dust shell, since it could be farther away if dust is condensing as an ejected shell expands and cools (e.g., Kochanek et al.

2011). This is, therefore, probably not dust that formed from the beginning of the 2012 eruption ~ 40 days earlier, because that material would be too close to the star. Expanding at around 550 km s^{-1} (Smith et al. 2010), the implied age is at least 1.1 yr, making it seem quite plausible that this dust formed from ejecta in one of its previous documented outbursts (see Mauerhan et al. 2012, Smith et al. 2010; Drake et al. 2010; Pastorello et al. 2013).² In any case, it should be noted that this hot CSM dust that contributes to the emission in the IR spectrum on Sep. 22 will not necessarily cause any corresponding absorption along our line-of-sight to the SN photosphere, since the geometry may be globally non-spherical or clumpy.

The contribution of this dust emission could weaken as time proceeds, either because some of the nearby CSM dust gets destroyed, or because the dust emission simply makes a smaller contribution to the total flux as the brightness of the SN photosphere increases.³ Both appear to be happening. By the time SN 2009ip reached its peak, it had a luminosity of roughly $1.3 \times 10^9 L_{\odot}$. The same dust that was at $R=120 \text{ AU}$ and 2000 K would then be heated to an equilibrium temperature of 4800 K (equation 1), vaporizing dust grains at that radius. (Moreover, the blast wave of the SN itself may have been approaching roughly the same radius by this point.) This destruction should happen as the SN brightens, but the IR excess might not disappear if there is additional dust at larger radii from previous outbursts that could be heated to the same temperature by the increasing luminosity. In fact, some IR excess emission does seem to persist. The magenta spectrum plotted against the Sep. 27 spectrum in Fig. 2 (top) shows the same contribution of hot dust at the same 2000 K temperature, except that the relative contribution of the dust is less. This smaller relative contribution from hot dust matches the spectral shape very well, especially the excess flux longward of $1.8 \mu\text{m}$, and mimics the appearance of a cooler photospheric temperature (6000 K vs. 7500 K at peak). A smaller contribution of hot dust may also be present even in the Oct. 14 spectrum around the time of peak luminosity, since it appears to have a small amount of excess flux beyond $2 \mu\text{m}$.

The mass of hot dust can be inferred from the IR excess if the grains are small ($a \lesssim 0.2 \mu\text{m}$; following Smith & Gehrz 2005 and Smith et al. 2008b), which for grains with a density of $\rho=2.25 \text{ g cm}^{-3}$ can be expressed as

$$M_d \approx 5 \times 10^{-7} M_{\odot} \left(\frac{L_d}{10^7 L_{\odot}} \right) \left(\frac{T_d}{2000 \text{ K}} \right)^{-6} \quad (2)$$

where L_d is the luminosity of the hot dust component at a temperature T_d . The 2000 K dust that contributes the IR excess in our pre-SN spectrum on Sep 23 has a luminosity $L_d \approx 9 \times 10^6 L_{\odot}$, although this comes with a large uncertainty of perhaps $\pm 50\%$ due to possible slit losses in the exposures of SN 2009ip or the standard star. Nevertheless,

² In this context, it is interesting to note that Foley et al. (2011) reported a similar $\sim 2100 \text{ K}$ dust excess around the LBV-like transient UGC2773-OT.

³ Note that our first spectrum was taken just 2 days before the rapid brightening, when the optical flux had faded by about 1 mag from the peak of the precursor event (see Fig. 1). This drop in flux from the underlying photosphere would serve to enhance the contrast of the IR excess from dust at this epoch.

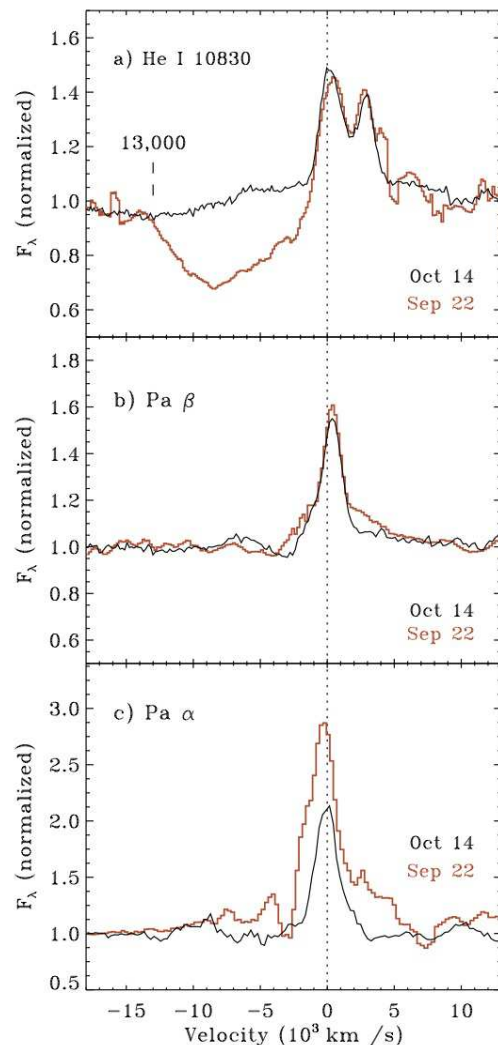


Figure 3. Individual line profiles before the sharp rise and soon after peak luminosity. (a) He I $\lambda 10830$, (b) Pa β , and (c) Pa α .

this provides a very rough estimate of the mass of hot dust of roughly $(3\text{--}6) \times 10^{-7} M_{\odot}$. This is, of course, only a lower limit to the total circumstellar dust mass because our near-IR data only trace the hottest dust, while a large additional mass of cooler dust may emit at longer IR wavelengths.

Lastly, we note that additional IR flux from free-free emission due to an ionized stellar wind, which often causes IR excess in hot stars (Wright & Barlow 1975), cannot explain the red color because the slope from free-free emission is too blue at the shortest IR wavelengths. The dashed brown curve in Figure 2 (top) shows the expected free-free IR emission from a constant-speed stellar wind.

4 LINE PROFILES

Line profiles for the three brightest lines in the IR spectrum are plotted in Figure 3, showing “before” and “after” spectra of He I $\lambda 10830$, Pa β , and Pa α taken at the same resolution with the FIRE spectrograph.

The most notable change in the line profiles is seen in

He I $\lambda 10830$. In the first epoch before the brightening, this line exhibits a very strong and broad P Cygni absorption trough extending to a blue edge of $-13,000 \text{ km s}^{-1}$. This is the same speed as seen in the blue edge of the P Cygni absorption in Balmer lines over the preceding week or so (Mauerhan et al. 2012). This broad He I absorption then disappears when the SN brightens to peak.⁴ Balmer lines show the same disappearance of the broad profiles at peak (Mauerhan et al. 2012), presumably for the same reason – i.e., the spectrum becomes dominated by opaque CSM interaction. The narrow emission components of He I $\lambda 10830$ show little or no change before and after the rapid brightening, relative to the continuum. The metastable nature of He I $\lambda 10830$ absorption makes it difficult to use it to draw conclusions about the relative He abundance in the fast ejecta, and there are few SNe IIn with comparable near-IR spectra for comparison.

Pa β and Pa α do not show any strong broad P Cygni absorption, as is seen in Balmer lines and He I $\lambda 10830$. There is a relatively faint underlying broad emission component to both Paschen lines, appearing as broad wings that weaken or disappear at the last epoch. The broad component makes a much stronger relative contribution to Pa α than to Pa β , which is the opposite of what is expected for electron scattering, where higher-order Paschen lines formed at higher optical depth have stronger electron scattering wings (Dessart et al. 2009). There is an apparent P Cygni absorption trough at roughly -3000 km s^{-1} in Pa α (with a width that is similar to the spectral resolution of our instrument), but it is difficult to judge the reality of this feature because of the strong telluric absorption in the vicinity of Pa α . As with He I $\lambda 10830$, the narrow components of the Paschen lines show little or no change with time, compared to the continuum, since they arise primarily in the CSM.

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⁴ Note that some significant portion (20–50%, depending on wavelength) of the near-IR continuum comes from hot CSM dust in an echo, rather than from the SN itself. This has the effect of diluting the apparent relative strength of emission/absorption lines. In other words, the IR emission/absorption features are stronger than they appear in this spectrum (i.e. the true intrinsic equivalent width is larger).